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AN APPLICATION OF RAY-TRACING TO SEISMIC EVENT LOCATION

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13. ABSTRACT

The objective of this study was to determine whether source modeling could improve teleseismic event locations near island arc structures, using models defined by available information about the underthrusting plates of these regions.

If one considers only the most reliably located events in the Aleutian Island arc, the teleseismic location shifts are all consistent with a simple plate model for the Aleutian-Alaskan region. This ~~consistency indicates that~~ source bias is the key factor in location errors for this region. Apparent unpredictability of the shifts for other events may stem from inaccurate knowledge of locations.

We describe a location method based on ray-tracing, using a crude source region plate model. In the case of the Aleutian-Alaskan region, this method predicts that all teleseismic locations should be shifted along the perpendicular to the Aleutian arc near the source location. The magnitude of the shift is estimated by a method which involves an initial hypocenter estimate, one calibration event anywhere along the island arc, and ray-tracing calculations of time residuals for sources near the estimated hypocenter. Our conclusion is that the technique shows promise of being able to remove location bias in island arc structures and should be investigated further.

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INTRODUCTION

The location of hypocenters using teleseismic station networks is routinely done with average earth travel-time tables together with certain statistical assumptions about velocity deviations from the tables. This report describes the possibility of extending the area near island arc structures in which calibration events can be used to reduce the location error. This approach is based on the idea that simple geological source models together with ray-tracing can be used to improve source location accuracy.

It is generally agreed that travel time residuals (the observed travel times minus the average earth travel times) result from contributions from the source region, crust and upper mantle in the detector region, and from lateral variations along the deep travel path. If one attempts to locate an event using a well-distributed network of teleseismic stations, and if the source region velocities have no azimuthal or depth dependent component, then accurate locations can be made, assuming that the travel time residuals are assumed to be normally and independently distributed with mean zero and a common variance at all stations. This assumption allows the effects of the local crustal and mantle velocity variations for the network of stations to be averaged out. The method is still valid for the case in which the source regions have velocities differing from those of the world average, but not depending systematically on the azimuth or depth.

The standard location methods first use an initial hypocenter estimate from which the residuals are computed at each of the stations. The least squares method then minimizes the sum of the squares of these residuals and makes an estimate of the corrected hypocenter latitude, longitude, origin time and focal depth (Herrin, 1960; Flinn, 1963; Cannon, 1966). With the assumption of linearity of the travel time curves for a small distance range (both in distance and depth) the corrected hypocenter is used as the estimate and the process is repeated until the desired convergence is obtained.

Refinement of this technique (Cannon, 1966) was made utilizing information that the measured variance in the residuals are not independent of station-to-source distance. These results were collected for a world wide distribution, and vary as indicated in Figure 1. The initial rise in residuals for stations at epicentral distances less than 40° reflects the fact that for these shorter paths the seismic wave spends a greater percentage of its travel time in the more non-uniform crust which increases the variance in the residuals. Therefore if the station residual is not shown for a particular source region the measured arrival time should be weighted in accordance with the appropriate variance for that distance.

Modifications to the standard hypocenter location method have been made in the past, but the variance of location was not greatly reduced (Wallace, 1970). The main deficiency of all of these hypocenter location methods is their inability to give accurate event

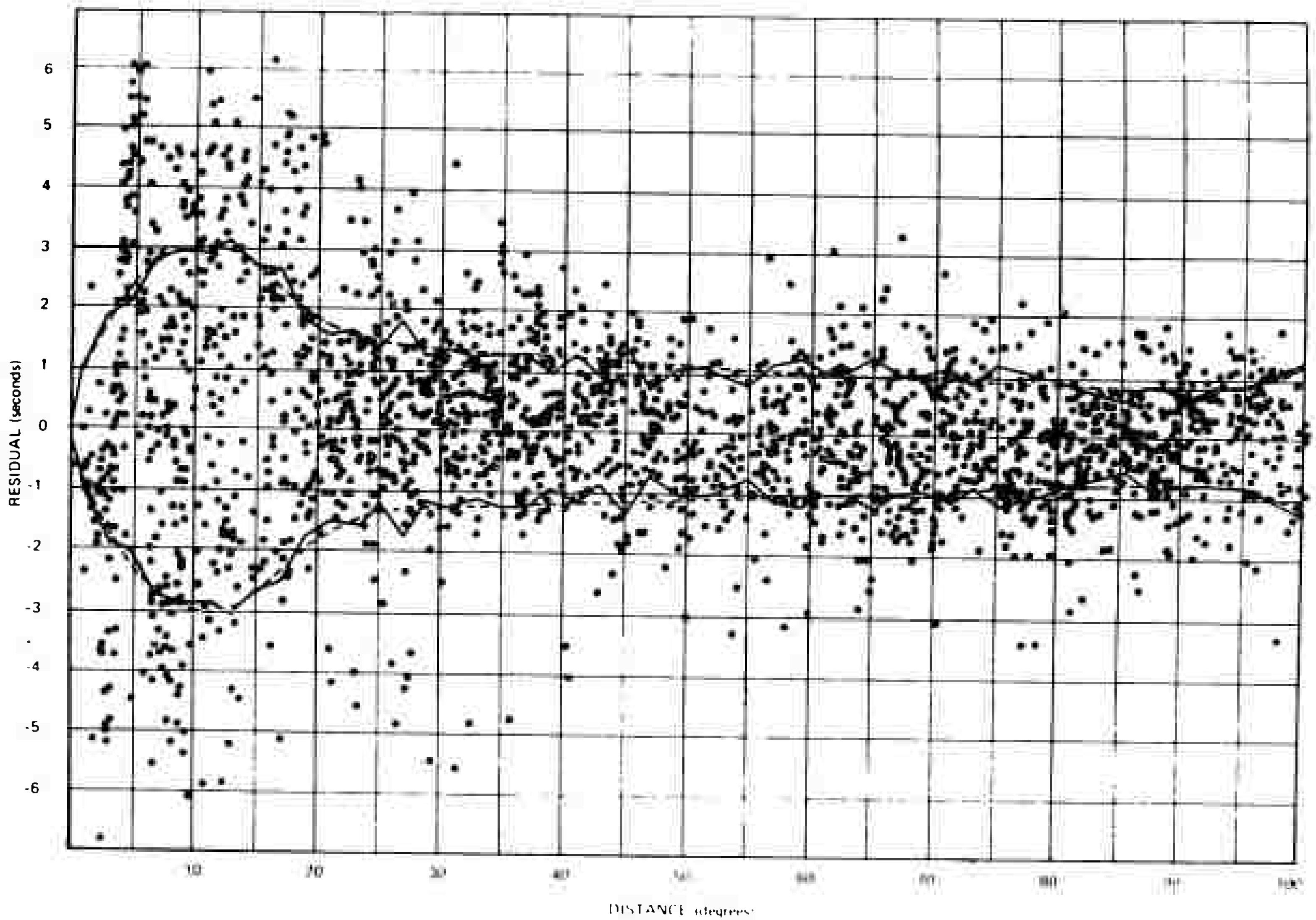


Figure 1. World residuals versus epicentral distance.

locations and depths in cases in which there are azimuthal velocity variations in the vicinity of the source.

USE OF CALIBRATION EVENTS

It is clear that if there is a high-velocity region north of an epicenter, a teleseismic network would interpret the early seismic arrivals to the north as though the epicenter were north of its actual location. The least-mean-square error location method can substantially reduce the effect of velocity variations in the vicinity of the stations, provided that a large number of well-distributed stations is available. This is not true, however, for variations in the vicinity of the epicenter. Only prior knowledge of this source region velocity distribution can correct for the apparent location shifts caused by lateral inhomogeneities near the source.

If one considers a reference event (1) and an unlocated event (2) situated near a high velocity region as is indicated in Figure 2, it is clear that the reference event arrival times can be used to correct the event (2) arrival times at this two dimensional network of stations. This is true since the seismic paths are similar for both events and travel time corrections made for all stations would be applicable over a large source region on the north side of the high velocity region. The use of calibration events is commonplace in location work and the source regions for which they are applicable range from a few to several hundred kilometers. As an example, Long Shot was used to locate Milrow within 1 Km (von Seggern, 1971); however, in this case the calibrated source region turned

out to be limited to the Amchitka Island vicinity (Chiburis, 1971a).

Event (3) of Figure 2, being on the opposite side of the high velocity region, would have shortened arrival times for the stations to the north instead of the south as for event (2), and thus the location shifts using the calibration event would be twice as large and in a direction opposite to the correct shift. This simple two-dimensional example of Figure 2 is intended to demonstrate that there is a considerable amount of uncertainty involved when using calibration events unless there is sufficient information about the source region, and also that the results can be completely unpredictable in complex source regions.

Much work has been done in the effectiveness of calibration events in a strictly statistical sense. Chiburis (1966, 1971a) establishes regional anomalies for Aleutian events. To achieve this along the Aleutian arc it is necessary to use many calibration events, and this implies the need for using well located earthquakes for calibration. This is a very difficult approach since epicenter location determination of earthquakes are commonly 10-20 Km in error. Thus, attempts to detect any reasonable regional dependence of the location shifts (vector from actual location to teleseismic location) in the Aleutians with poorly located events have been disappointing. One might expect the Long Shot anomalies to calibrate adjacent regions approximately, but they prove to be useful only in the immediate vicinity of Amchitka Island (Chiburis, 1971a).

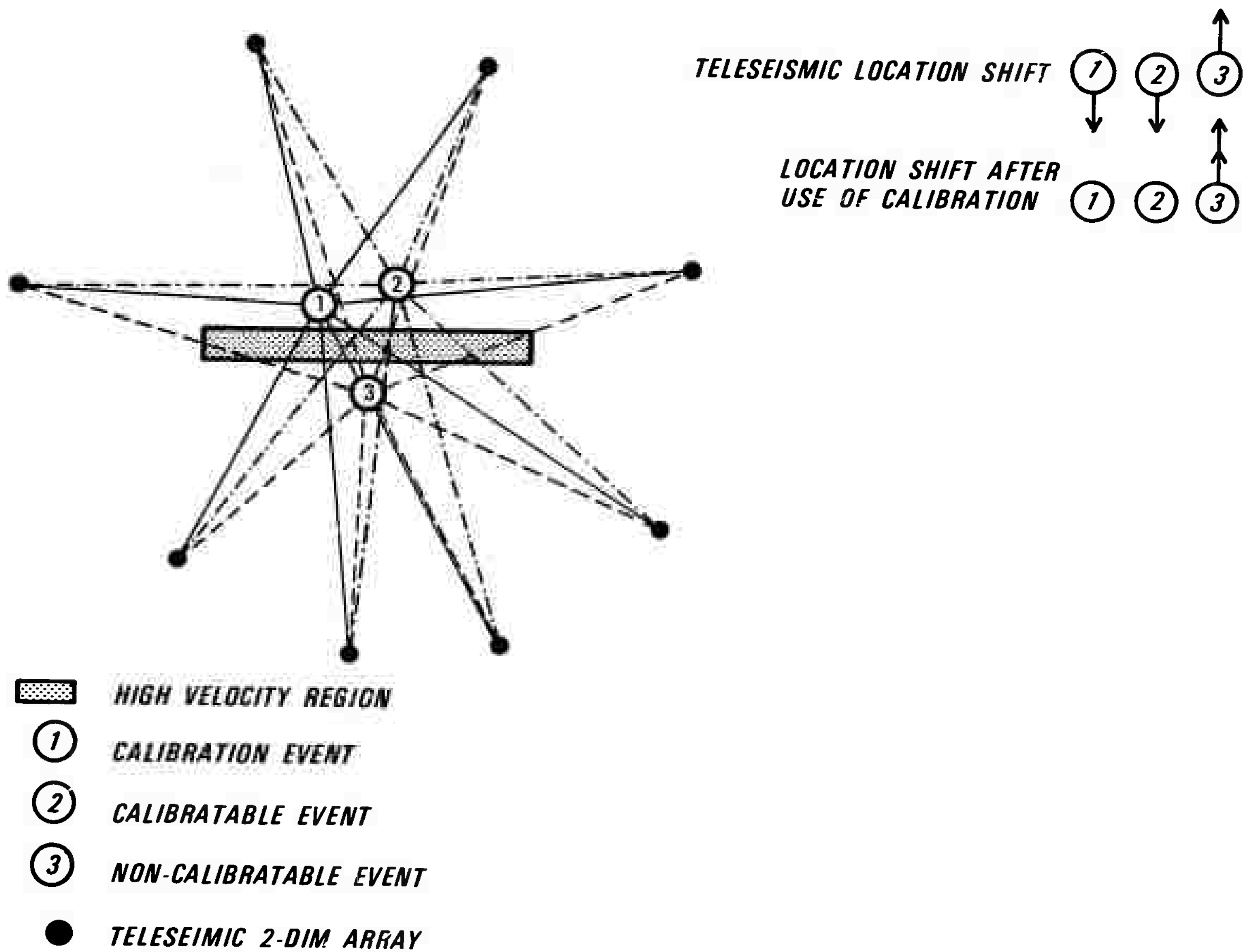


Figure 2. Use and mis-use of calibration events.

The use of calibration events for each of the many regions which seem to have common anomalies is the only reasonable alternative short of taking into account the geology of the source region. More advanced attempts were reported (Chiburis, 1971a) which derived the spatial functional dependence of the anomalies. Although this seems to be a step forward the method is still plagued with the problem that the true location shift pattern is hidden because of the large error in the presumed known locations of earthquakes used to define the pattern.

INTERPRETATION OF LOCATION SHIFTS USING A SOURCE REGION MODEL

In this section we show that the location shift pattern throughout the Aleutian arc is of a much simpler nature than the spatial function analysis would indicate. To see this one must be careful to use only the events which have well-located epicenters ($\pm$ 4 Km error); this amounts to ignoring the location shifts of almost all the earthquakes in this region. For the Aleutian Islands region one has the following set of events with a location uncertainty of less than 4 Km:

a. Long Shot, Milrow and Cannikin all have precisely known hypocenters but unfortunately are within 10 Km of one another and the three shots therefore give little more location information than only one shot. All three shots were mislocated in the same direction and magnitude using a large well distributed world net (300 stations). The teleseismic location of Long Shot (detonated 29 October 1965 at 51.438°N, 179.183°E) was 22 Km almost due north of its actual location.

b. The Flexbag event was set off 6 September 1968, approximately 70 Km southwest of Long Shot. Since Flexbag had an equivalent of only 310 tons of TNT, the same large networks used for the three nuclear shots were not available; 31 stations with an azimuthal distribution of 221°, were common to Flexbag and Long Shot.

With this smaller common network, both Long Shot and Flexbag were located (without anomalies) using the

program SHIFT (Chiburis 1968) and both events were mislocated in a very similar direction and amount. The shift calculated by the 31 station network was 13.7 Km at 315° azimuth for Long Shot, and 15.6 Km at 342° for Flexbag (Chiburis, 1969). The close similarity in mislocation suggests that both source regions, separated by 70 Km, contain a similar bias. The fact that the 31 station network mislocates Long Shot by a significantly different amount (16 vs 22 Km), but essentially in the same direction, is not an important difference for the type of evidence being accumulated. The fact that a common network mislocates them the same way is the result to be emphasized. Presumably the larger network would change the Flexbag location in the same way the Long Shot location changed.

c. Chiburis (1971b) isolated a set of well-located earthquakes in Central Alaska to investigate the variability of the travel time anomalies as a function of position in this region. The location of the 12 events were well established and consistent using the local networks and the locations are given better than 4 Km. In Figure 3 one sees that there is a great deal of consistency in the location shifts (the directions and amounts being comparable) of the southernmost six events. The six more northern events have very little similarity among themselves and with the other group of six.

The manner in which all of the Alaskan events, Long Shot, and Flexbag mislocate will be shown to be explainable in terms of a source model for these regions.

The list of well located events now consists of the nuclear events of Amchitka Island, Flexbag (70 Km southwest of Amchitka Island) and 12 well located earthquakes distributed over central Alaska. The multitude of earthquakes throughout both of these regions are known to be commonly in error by 10-20 Km and it is felt that this can easily mislead one's analysis if attempts were made to explain these location shifts.

Engdahl's network near Amchitka Island might aid in the gathering of more well located events, but even events within his net (Engdahl, personal communication) sometimes have location errors of 5.0-10.0 Km, and the accurately located events are too near Amchitka to be of importance in this study.

The overall situation is indicated in Figure 3. One notes that all the location shifts but the northernmost six are perpendicular to the arc defined by the seismicity in the Aleutians, and that the amount of the shifts in Alaska are 14 Km rather than 22 Km for Long Shot and Flexbag. Interpretation of the location shift direction, change in amount of the location shift, and the disagreement of the northernmost events with the shift pattern can be achieved using a tectonic plate model with only the plate parameters presently available for the different island arc regions.

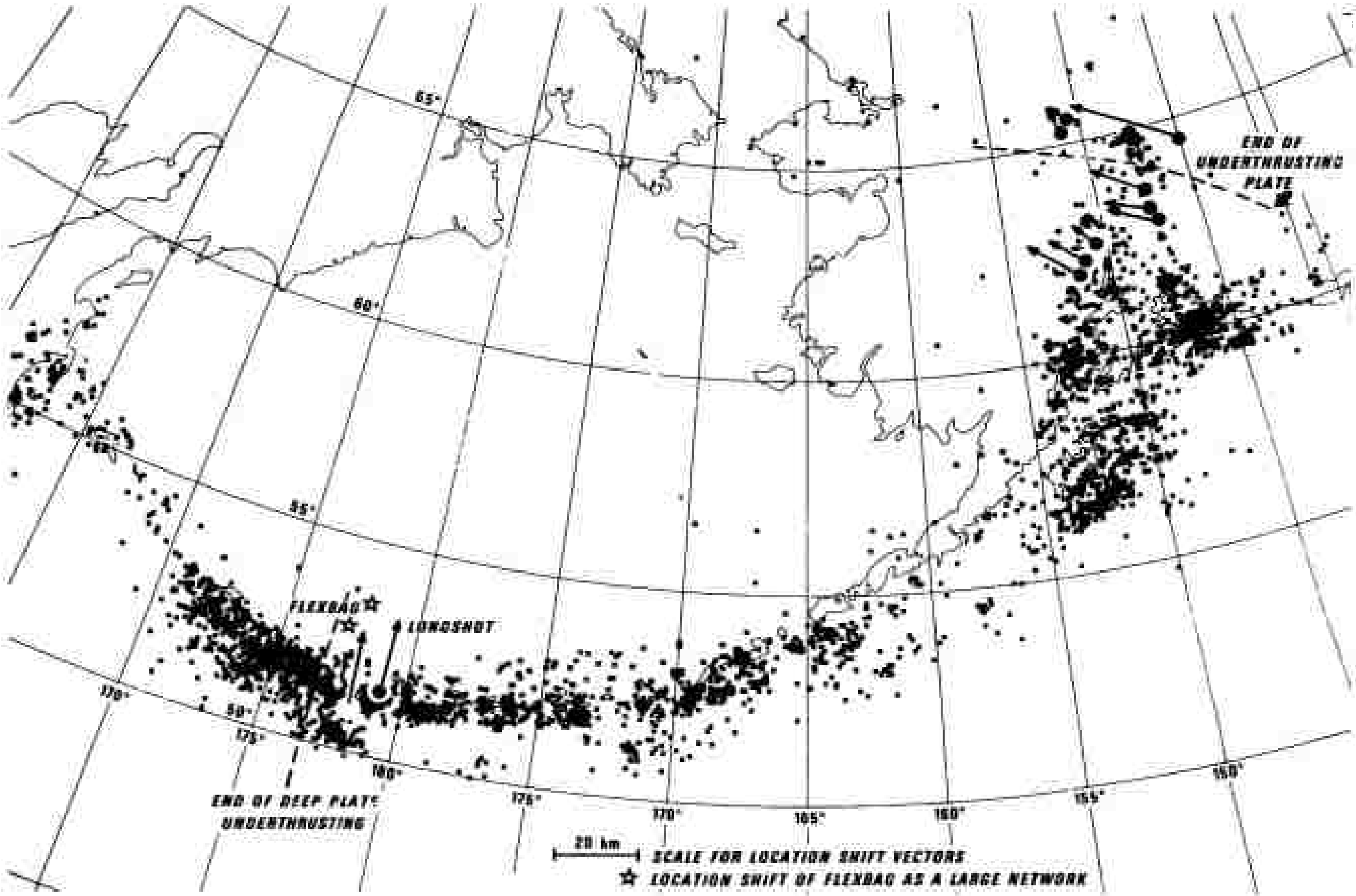


Figure 3. Seismicity and location shifts for Aleutian-Alaskan region.

PLATE MODEL FOR ALEUTIAN REGION

The spatial distribution of earthquake hypocenters, together with information about the location of the trench and active volcanoes, can be used to define the geometry of the dipping lithospheric plates in regions such as the Aleutians (Oliver and Isacks, 1967). This information should define the maximum depth of penetration, the dip angle and the plate position (Isacks et al., 1968).

The depth contours defining the plate and its northerly dip are shown in Figure 4. As the seismicity chart of Figure 3 shows, these contours should be continued into the Central Alaskan region where the plate structure probably ends. This seismicity pattern which continues into Alaska is also accompanied with the string of active volcanoes (which are all located just beyond the 100 Km depth contours (Coats, 1962) and the Aleutian Trench (Isacks et al., 1968). Figure 3 also shows that at about 177°E longitude the maximum depth of plate penetration decreases to less than 100 Km. This is associated with the absence of active volcanoes east of this point in the Aleutians. Thus the geometry of the dipping plate differs in this region, at least in the maximum depth of penetration into the mantle. This difference in penetration is understandable in terms of tectonic theory as the result of the location of the poles of rotation of the Bering Sea and Pacific plates. There is essentially a head on collision of the two plates in the regions having the deepest penetration.

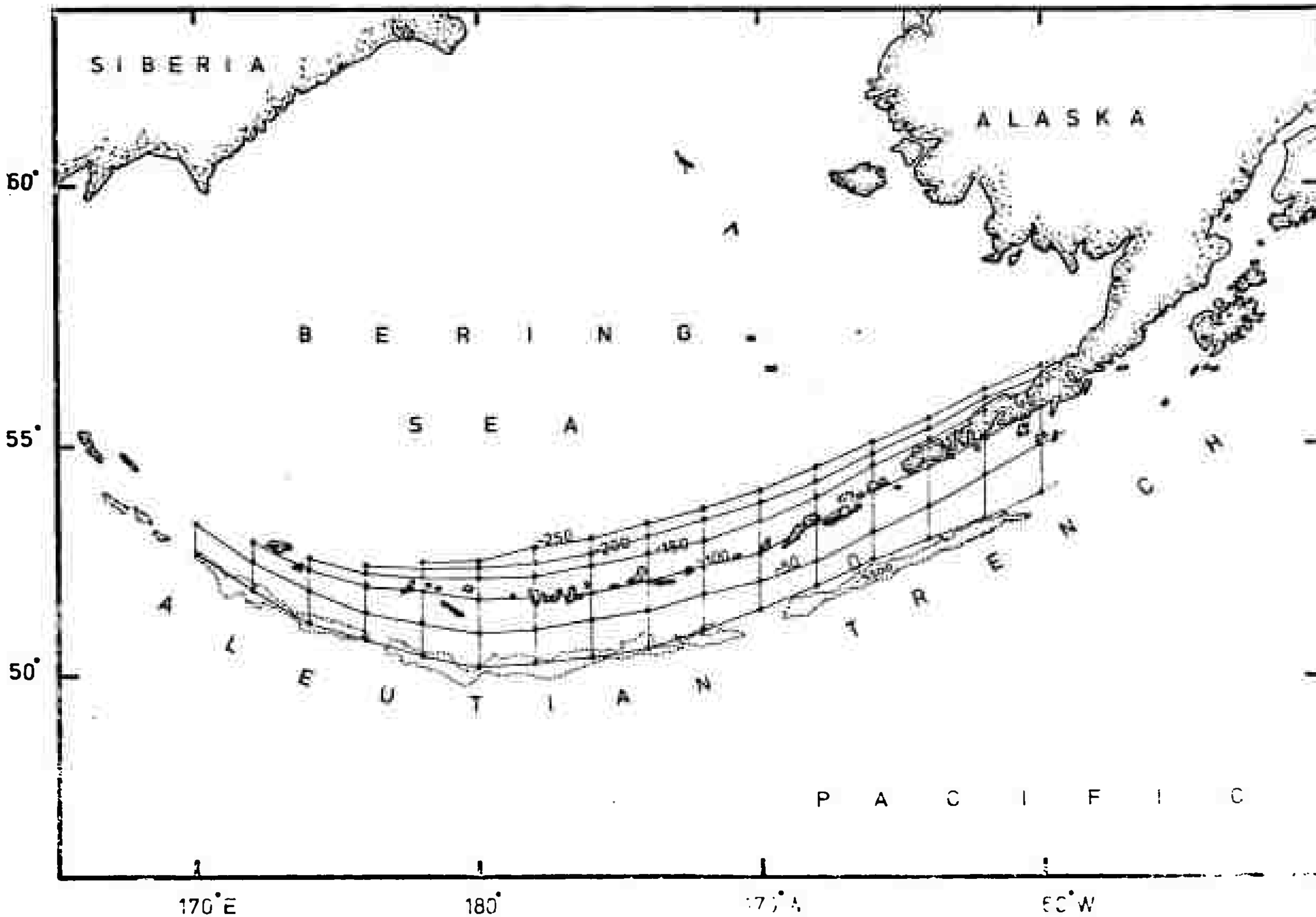


Figure 4. Earthquake depth of focus contours in the Aleutians.

In the eastern part of the Aleutians the relative plate motion is more of a glancing one and the underthrusting is reduced (LePichon, 1968; Dewey, 1970).

Figure 3 also shows that in Central Alaska the earthquakes are spread over a larger area, and since the maximum penetration is the same, it implies that the plate is dipping at a shallower angle. This agrees with the information indicating that the trench to active volcanoes distance is greater. Thus, the plate penetration and dip angles are seen to differ along the Aleutian Arc into Alaska; however, there is indication that although the geometry differs, the plate composition is similar (or would be expected if it were all one ocean crust; Jacobs, personal communication).

Figure 5 shows a cross section of the depth of focus for earthquakes recorded by Engdahl's net (Engdahl, 1971) near Amchitka Island. One sees the underthrusting plate dipping at approximately 45°, having a width of 80 Km and thrusting to depths of 250 Km. Estimates of the compressional velocity in the plate, and more detailed descriptions of variations within the plate, have a greater uncertainty. Plate velocities are usually assumed to be 7-10 percent higher than the surrounding mantle velocities. The variation in the plate temperature (and thus the velocity) along the Aleutian Arc is another uncertain parameter but these variations are not likely to be large. Errors of a few percent in the estimates of velocity contrast between the plate and surroundings would result in substantially incorrect residuals.

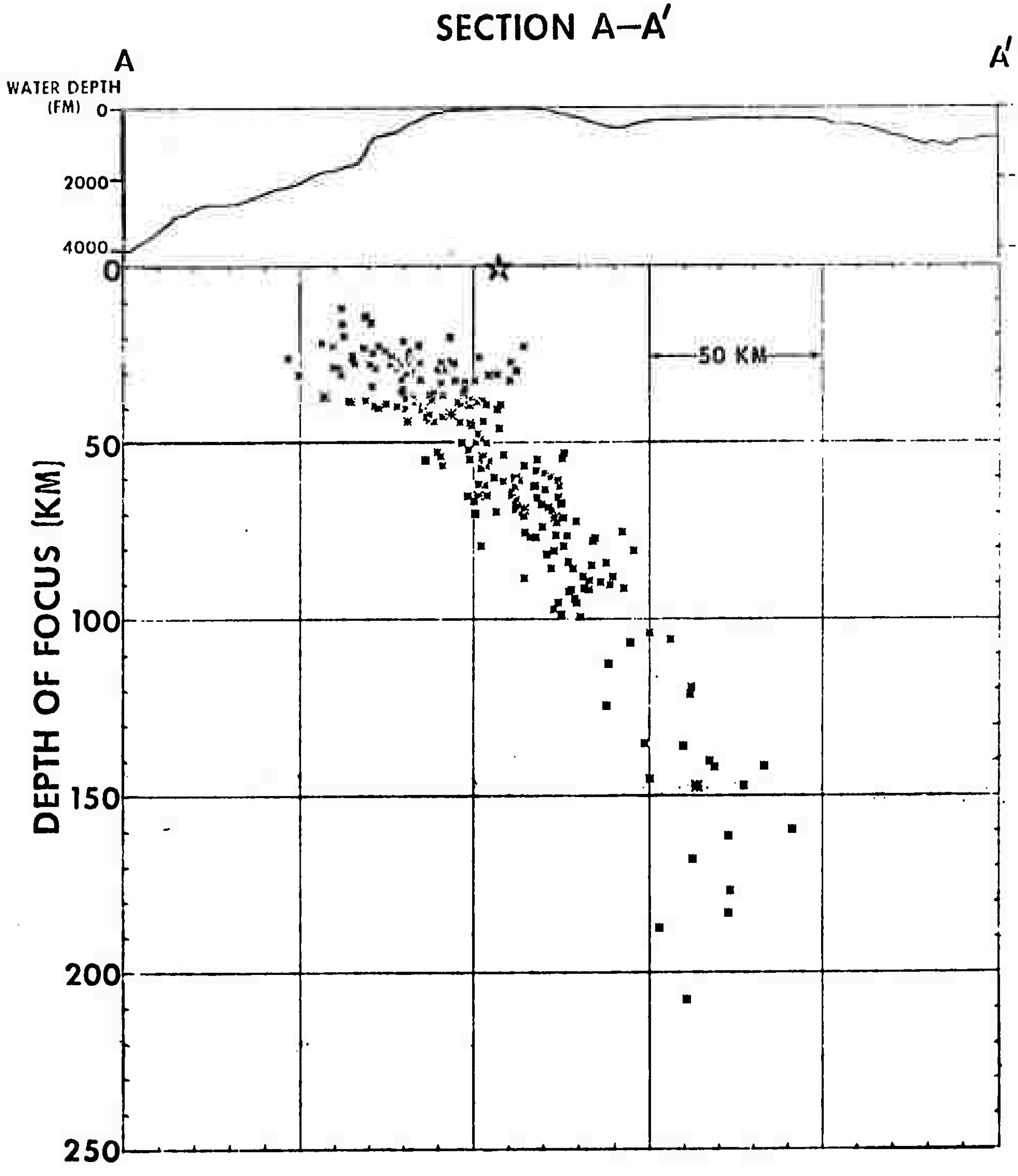


Figure 5. Earthquake depth of focus profile near Amchitka.

This makes it necessary to use calibration events (e.g. Long Shot) along with the model in order to derive reliable location corrections.

Jacob (1971) tried about 30 different plate models in an effort to obtain a model which fits the world-wide residuals observed from Long Shot. He arrived at an Aleutian plate model having a shallow dip down to approximately 100 Km depth (below Amchitka) and continuing at a steeper dip angle down to approximately 250 Km. This model and the ray paths from Long Shot which are located in the vertical plane perpendicular to the arc are illustrated in Figure 6. In this figure various features of the ray paths are indicated. Rays with large take-off angles (measured from the downward vertical), 27° in this case, propagate just above the plate to epicentral distances less than 30°. Rays with smaller initial take-off angles glance off the plate and are refracted upward to emerge at similarly small epicentral distances. This upward deflection of energy produces a zone of low energy density. Rays with even greater initial take-off angles penetrate the higher-velocity plate, travel the greater part of its length, and emerge at teleseismic distances as early arrivals (negative residuals). Rays with near vertical take-off angles are refracted downward, producing another shadow zone at larger epicentral distances. Rays initially propagating toward the south undergo little refraction by the plate and travel only a short distance through it, thereby being detected with smaller negative residuals. The majority of the rays have take-off angles outside

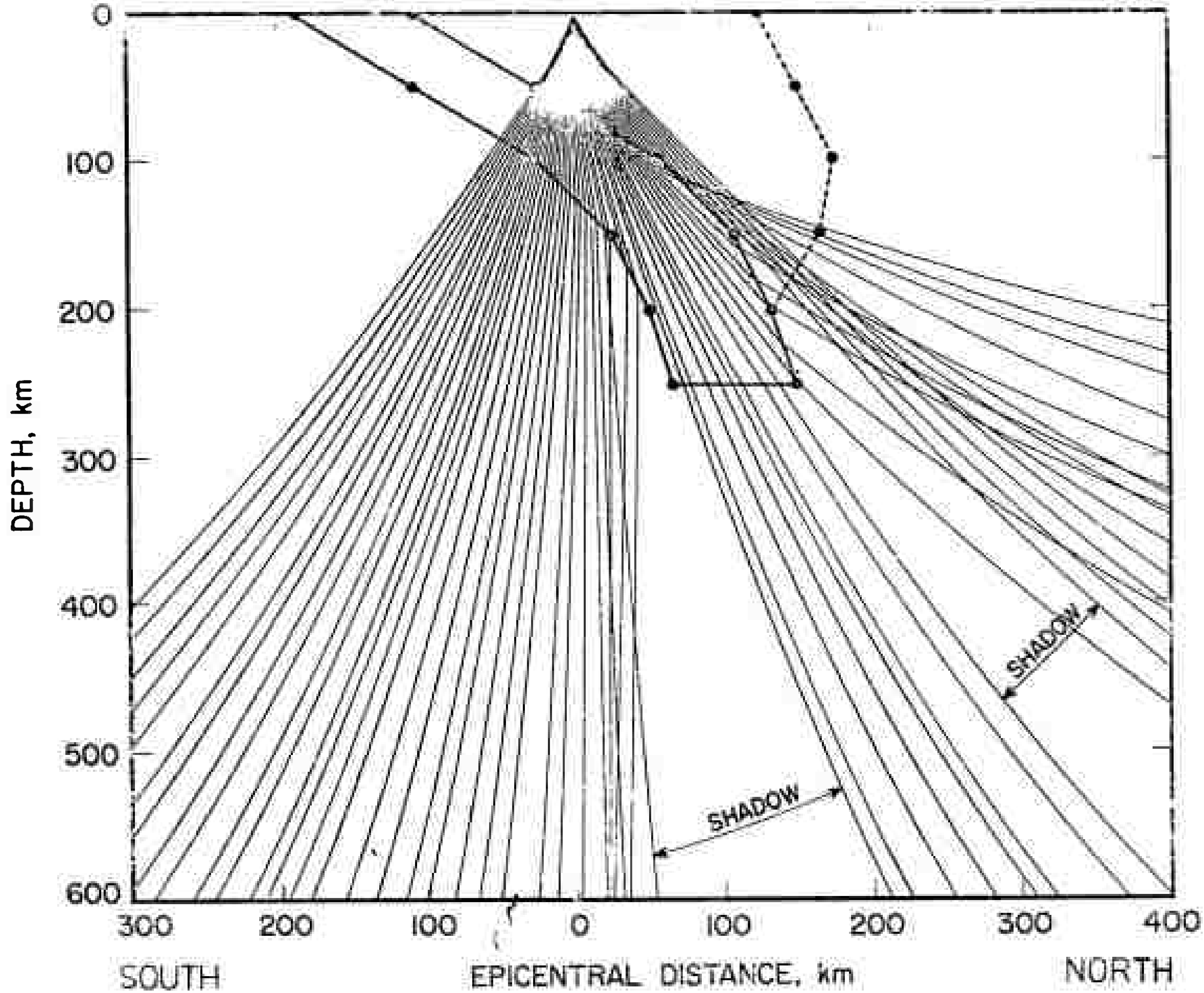


Figure 6. Ray tracing in Jacobs plate model.

this north-south vertical plane, but these are more difficult to characterize.

USE OF SOURCE MODEL TO CORRECT LOCATIONS

The major effect of the plate is that seismic rays traveling south travel a shorter distance in the higher-velocity plate than those which travel northward, and therefore the teleseismic location is shifted north. This explains why the direction of the mislocation vectors shown in Figure 3 are all perpendicular to the plate arc. Also shown in this figure is the zone of deep earthquakes which ends just south of the northernmost six events in Alaska. The underthrusting plate is not present in this region, and those six events are not in a plate source region structure; hence it is clear why the location shifts of these events cannot be explained in the same manner.

That the location shifts are all perpendicular to the Aleutian arc is good evidence that the presence of the underthrusting plate is the dominant factor in the mislocation. From this evidence there is reason to believe that all events near this arc should be relocated in a similar fashion.

This should be true for events at all depths to approximately 200 Km in the plate vicinity. As emphasized before, events which seem to relocate in a different direction are ones which are not accurately located by the regional station networks.

The amount of the location shift for these events is a function of the plate geometry and the location of the event relative to the plate. Intuitively one sees that as the source depth increases, the seismic wave

travels a shorter distance in the plate, thus reducing the negative residual. It is therefore not surprising that the location shifts of the Alaskan events are less than those of Flexbag and Long Shot, since these Alaskan events are approximately 100 Km deep. (Chiburis, 1971). While the direction of the location shift relative to the arc will always be the same, ray-tracing is expected to give good estimates of the location shift amounts relative to the Long Shot shift as functions of the source position and depth.

The shifts of the six more southern Alaskan events plotted in Figure 3 are 11.9, 14.3, 9.2, 11.1, 13.7, and 16.6 Km (Chiburis, 1971b). All these events are estimated to be at approximately 100 Km depth, and therefore are expected to shift by roughly the same amount, which seems to be the case when one considers the actual location error to be approximately 4 Km.

In order to estimate the shift by ray-tracing, rough estimates of the source epicenter and depth are needed (knowledge of the epicenter to within about 20 Km and depth to 50 Km). Using this approximate source location one then determines the set of residuals for arrivals at various azimuths and epicentral distances (by ray tracing) and inputs these residuals into a location program to obtain a corrected location. This has been done for various source locations and depths.

These location shifts are then corrected using a factor determined by the location shift of a calibration event such as Long Shot and the observed location shift of each event. This is done in order to make a

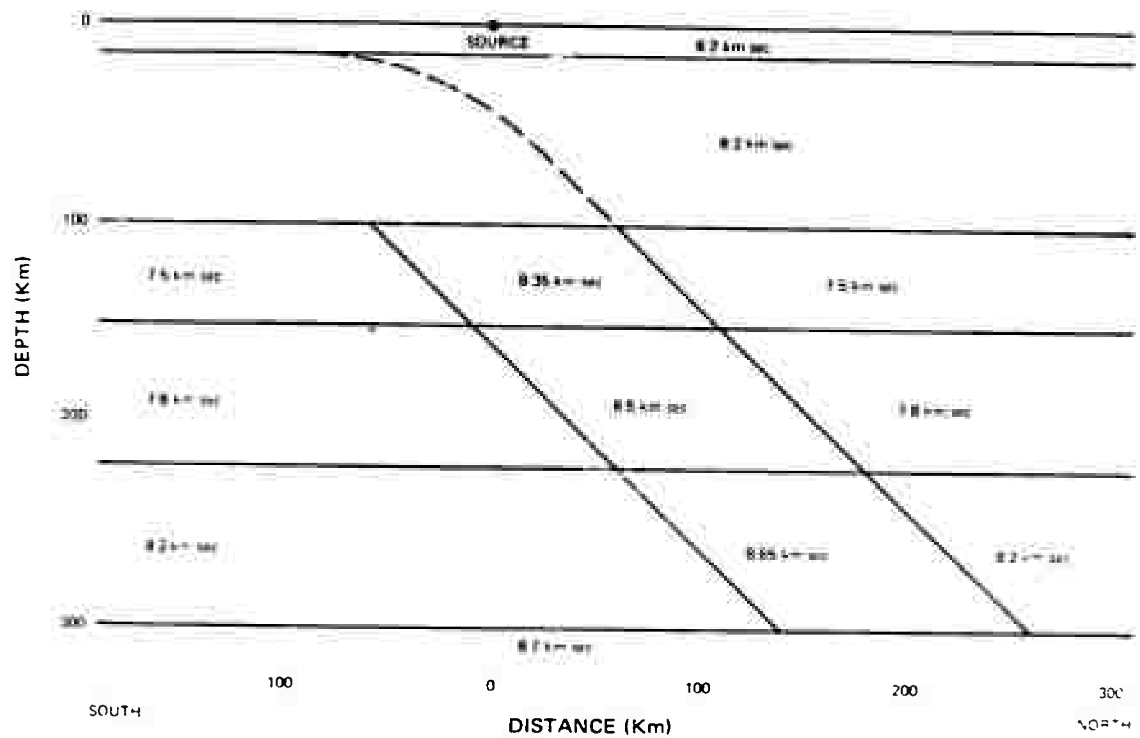
first-order correction for the inaccuracies of the assumed plate velocities, and also to some degree account for the uncertainty in the plate geometry.

For the purposes of the location scheme it may not be necessary to use a model as elaborate as Jacob's. A simplified plate structure such as that used by Sorrels' ray-tracing program together with the upper mantle and crust are modeled, and the remaining earth is assumed to be that used for the Herrin travel time tables.

Figure 7 shows one of the plate structures used by Sorrells (1969), indicating the position of Long Shot. In Sorrell's structure the background velocities (those surrounding the plate) are slower than that of the world average upper mantle and crust, but are the best velocity estimates for the Aleutian region. These slower velocities give rise to large positive residuals for rays which do not travel through much of the plate. In contrast, Jacobs used P68 travel times to construct his upper mantle and crustal model. The world distribution of residuals for a complete set of source positions and depths has been calculated using Sorrells' model.

Figures 8 through 13 show the residuals, for some of the source locations, as a functions of source-to-receiver azimuth. Since there is symmetry about the axis to the north it is only necessary to indicate the results from 0°-180°.

Figure 14 shows schematically various source positions used in relation to the plate. Various source depths were used for some geographical positions.



(a)

Figure 7. Sorrells' plate model structure.

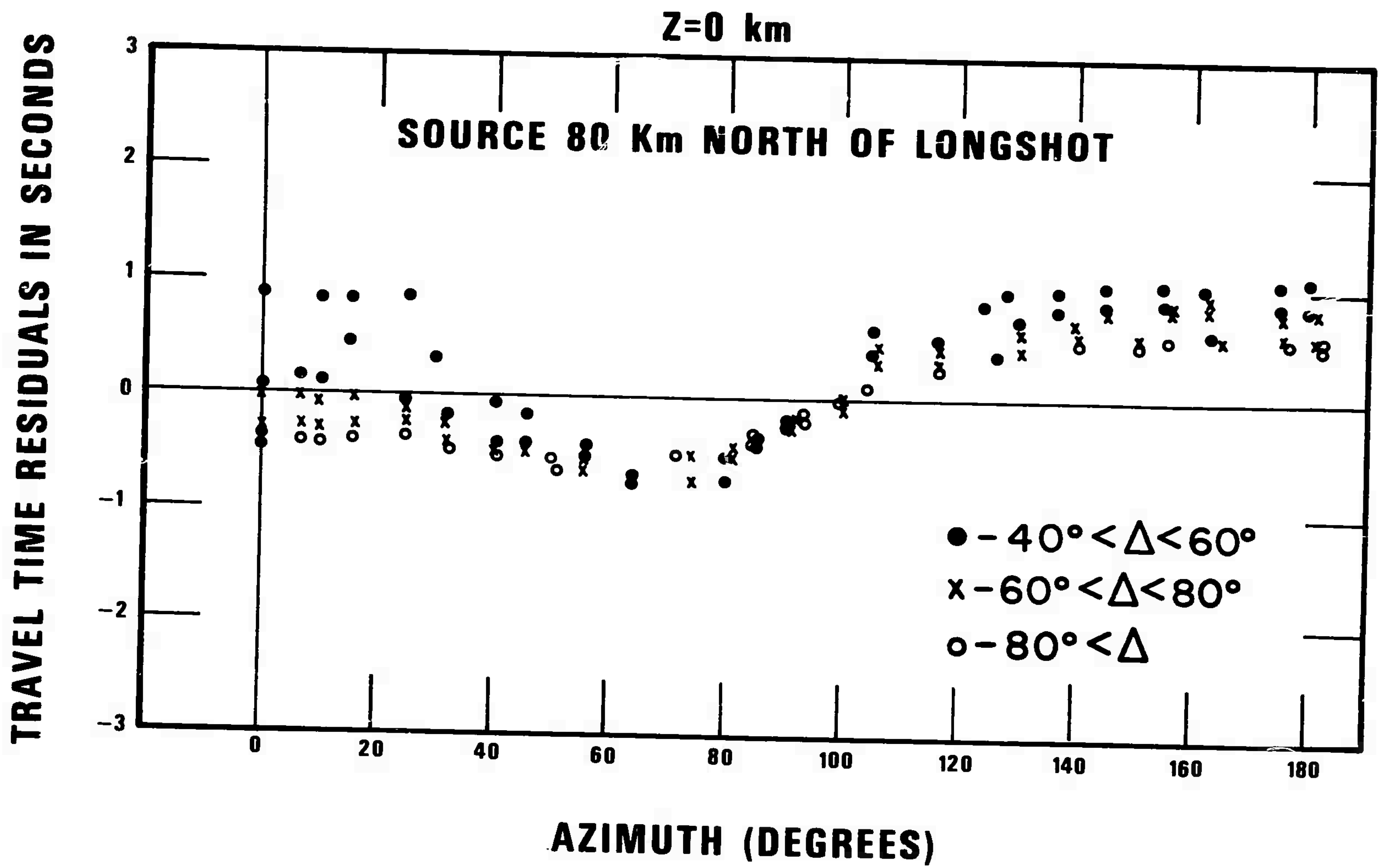


Figure 8. Calculated residuals vs azimuth.

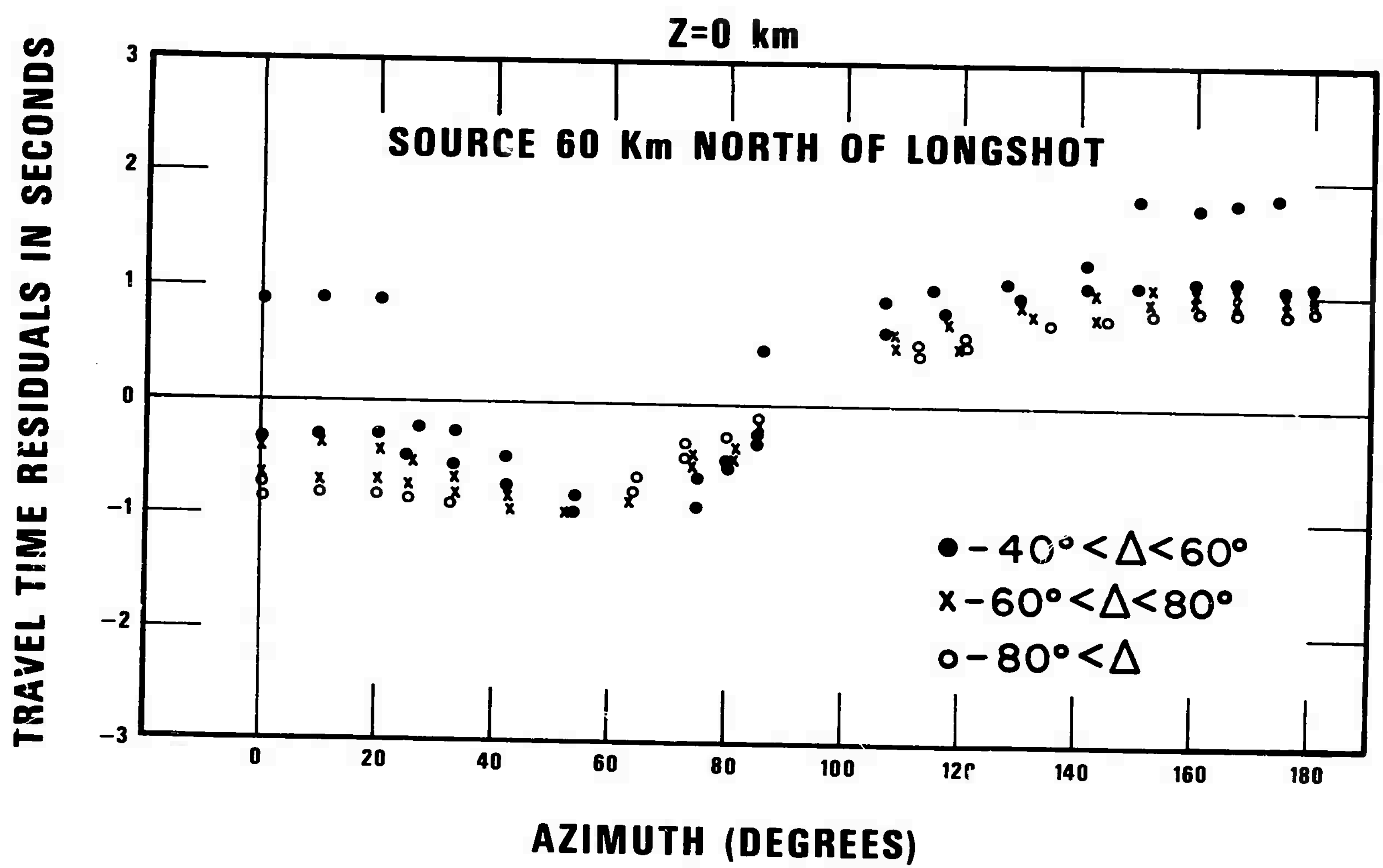


Figure 9a. Calculated residuals vs azimuth.

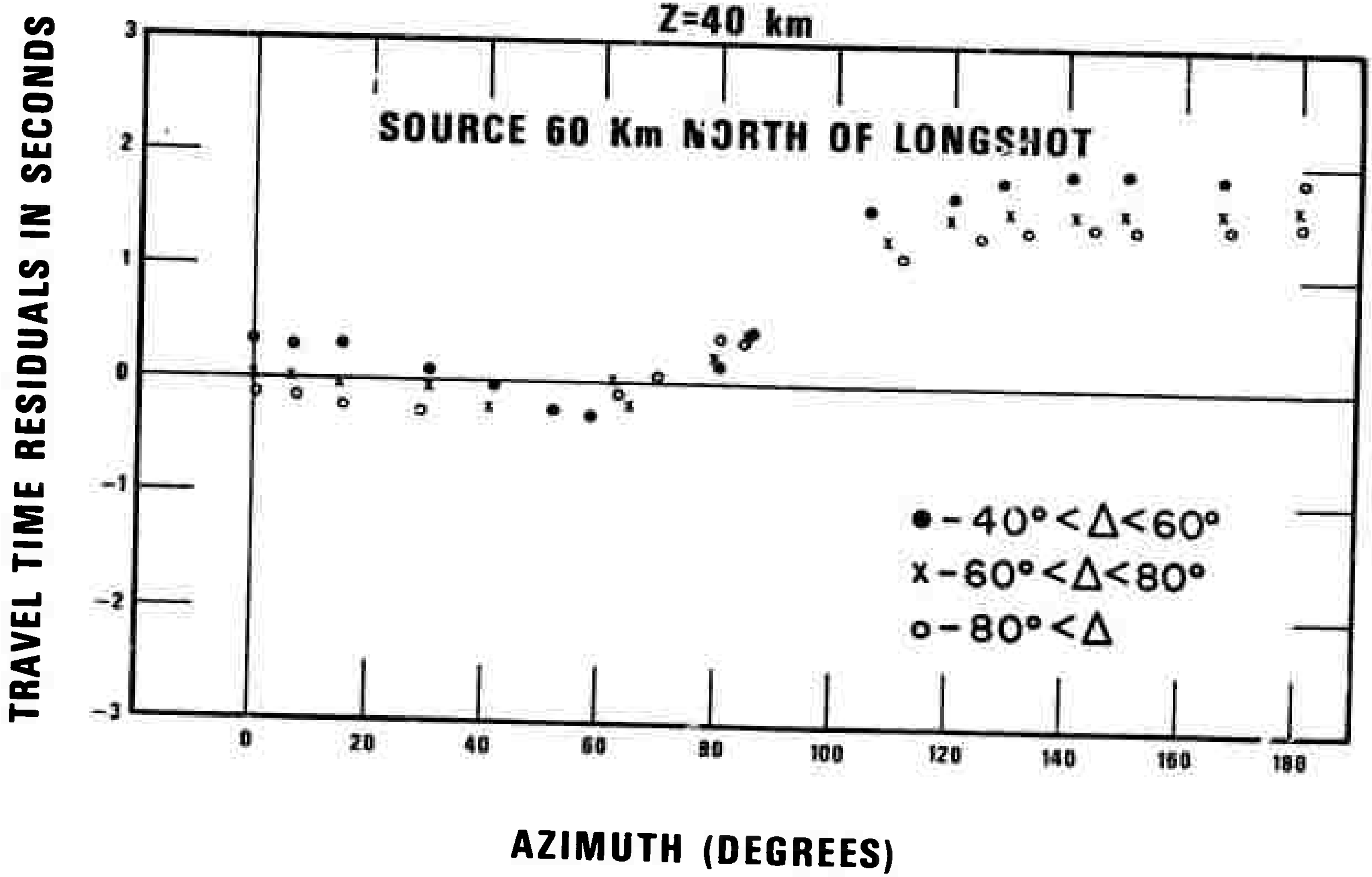


Figure 9b. Calculated residuals vs azimuth.

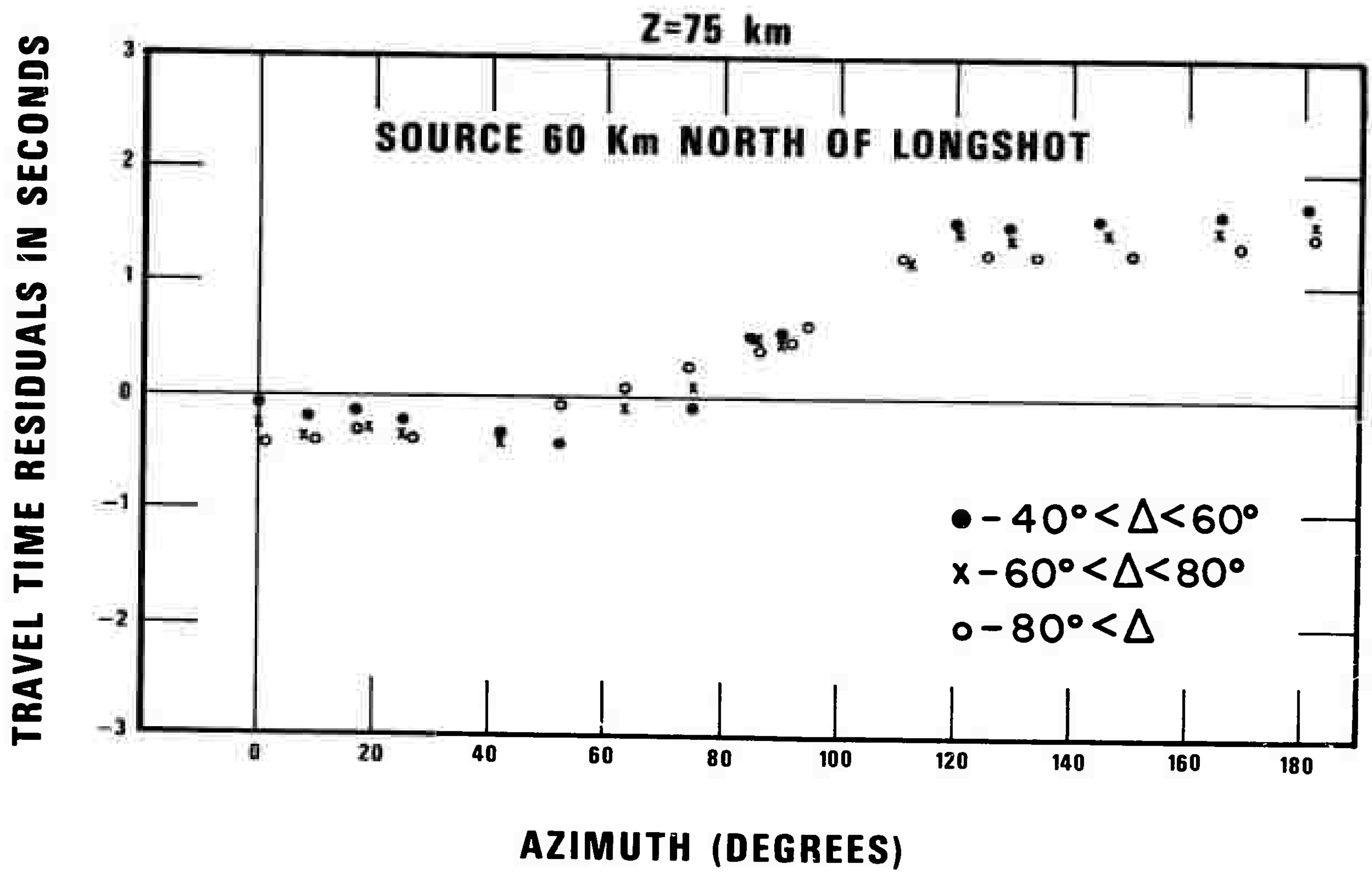


Figure 9c. Calculated residuals vs azimuth.

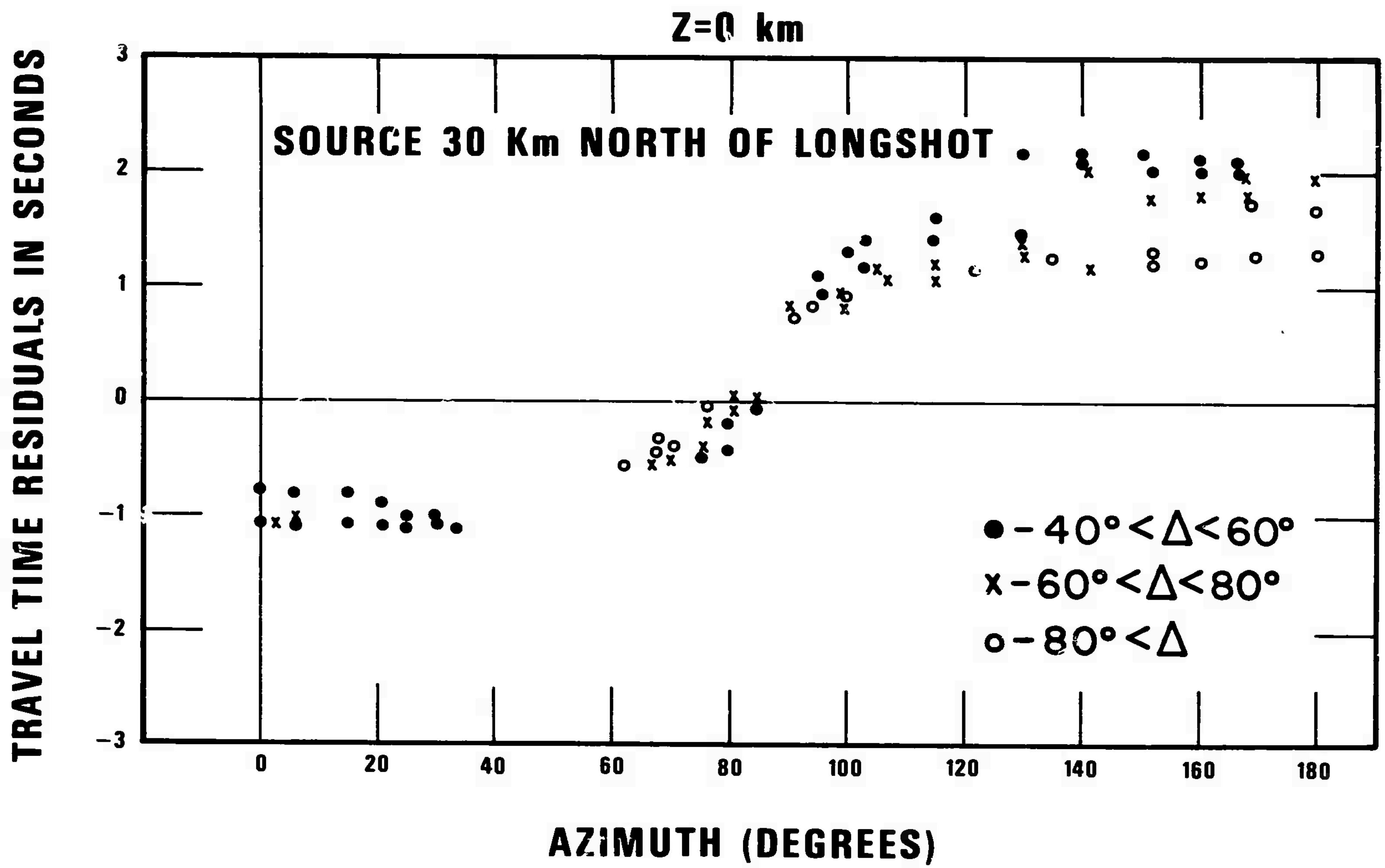


Figure 10a. Calculated residuals vs azimuth.

16g

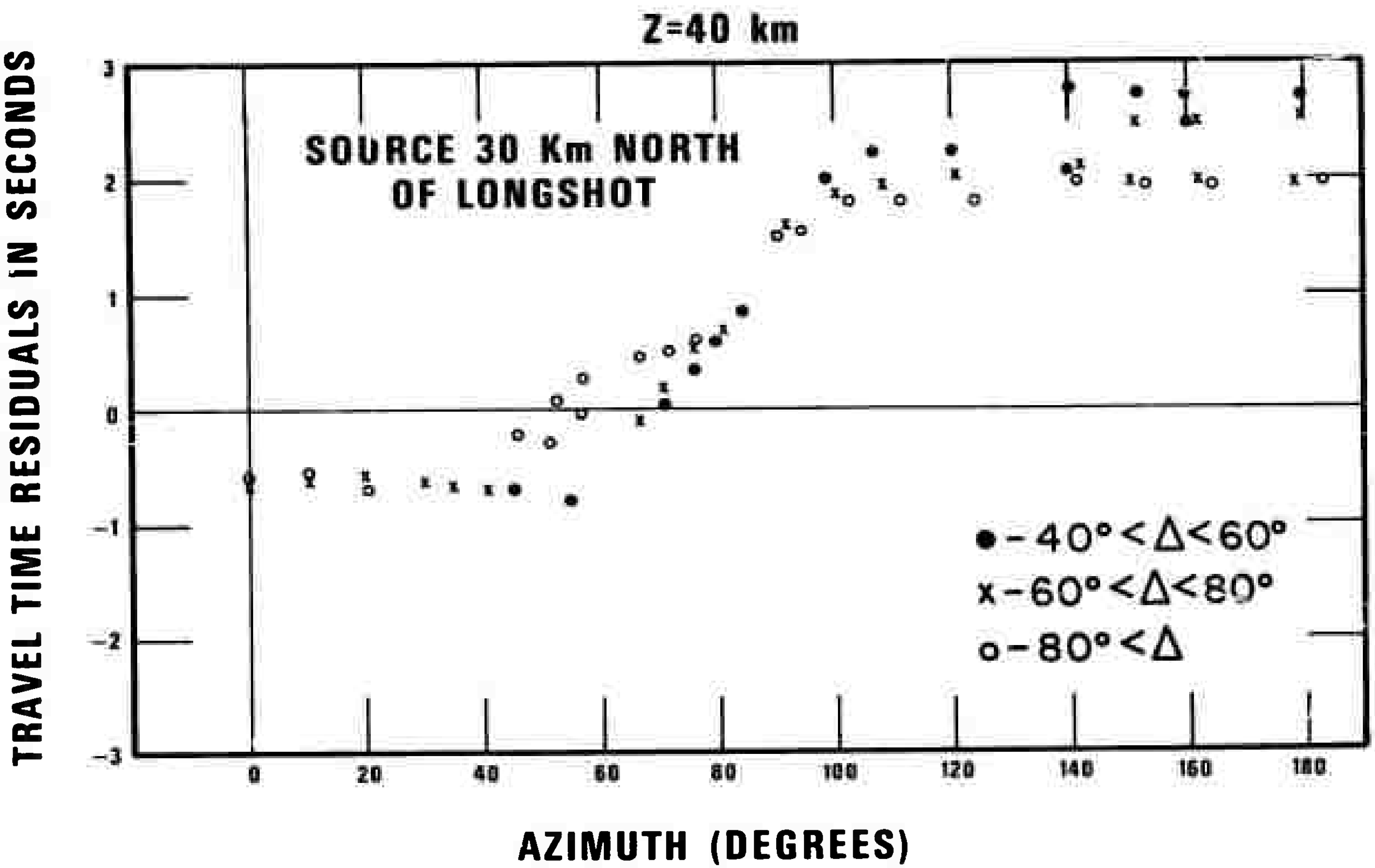


Figure 10b. Calculated residuals vs azimuth.

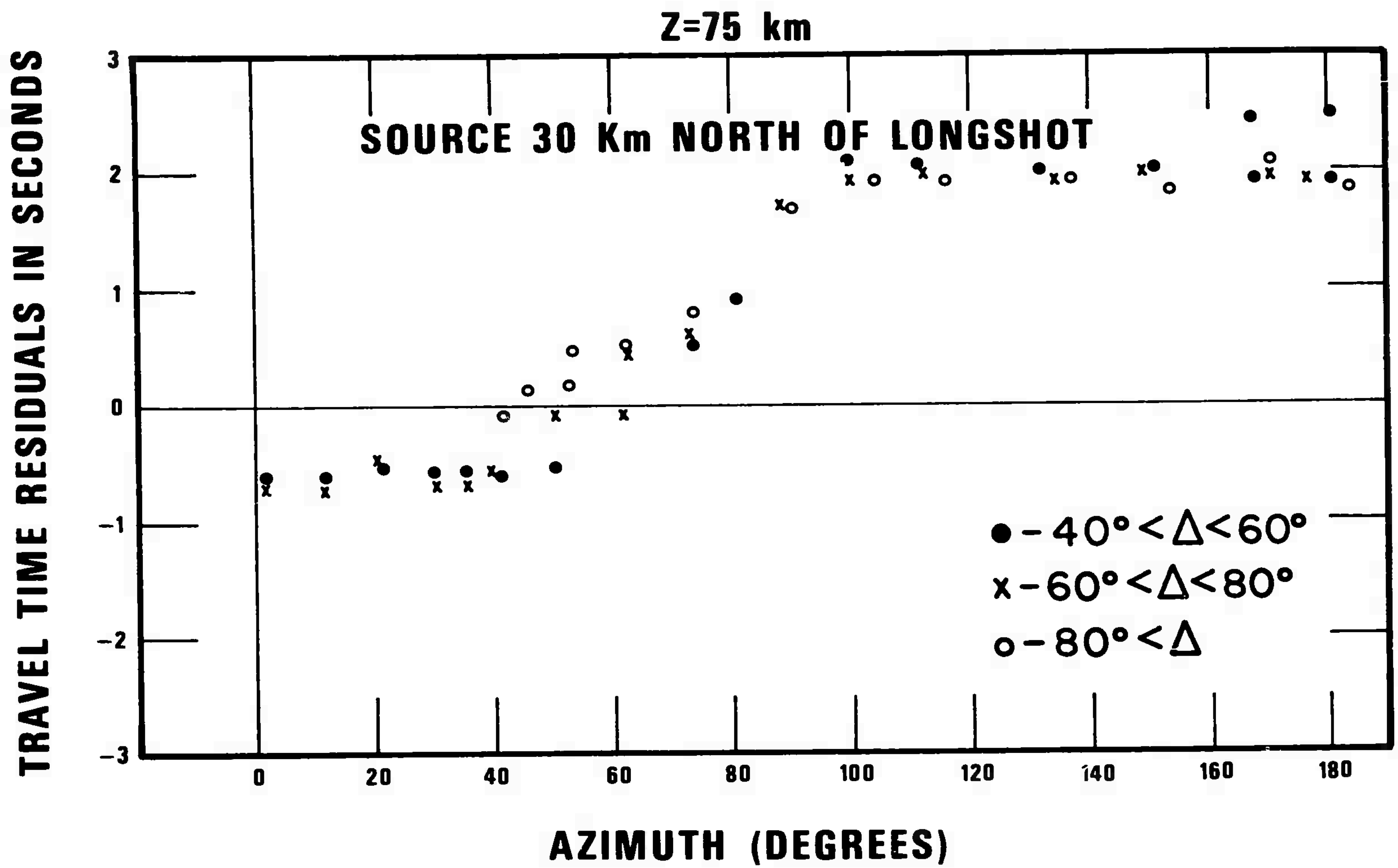


Figure 10c. Calculated residuals vs azimuth.

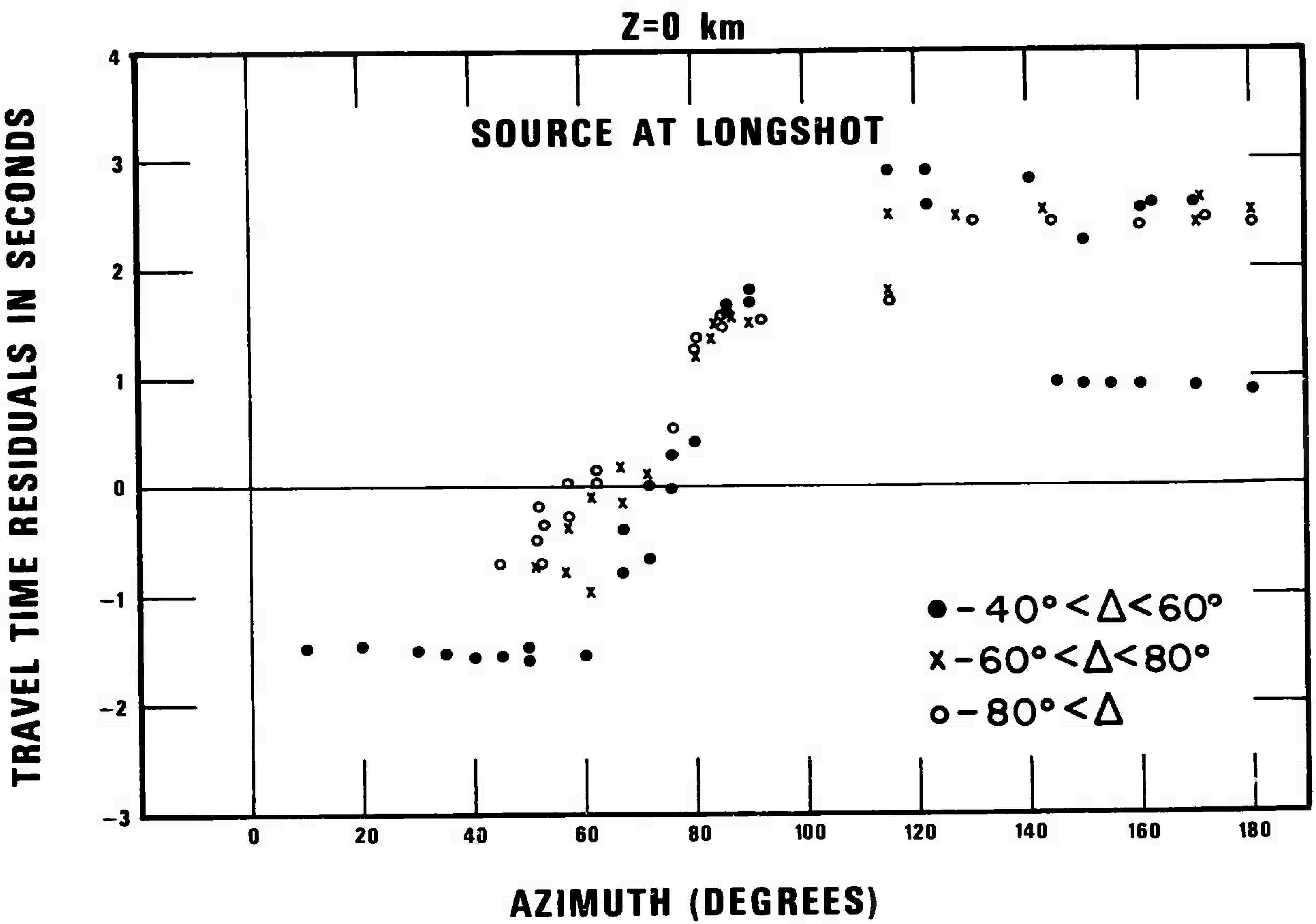


Figure 11a. Calculated residuals vs azimuth.

165

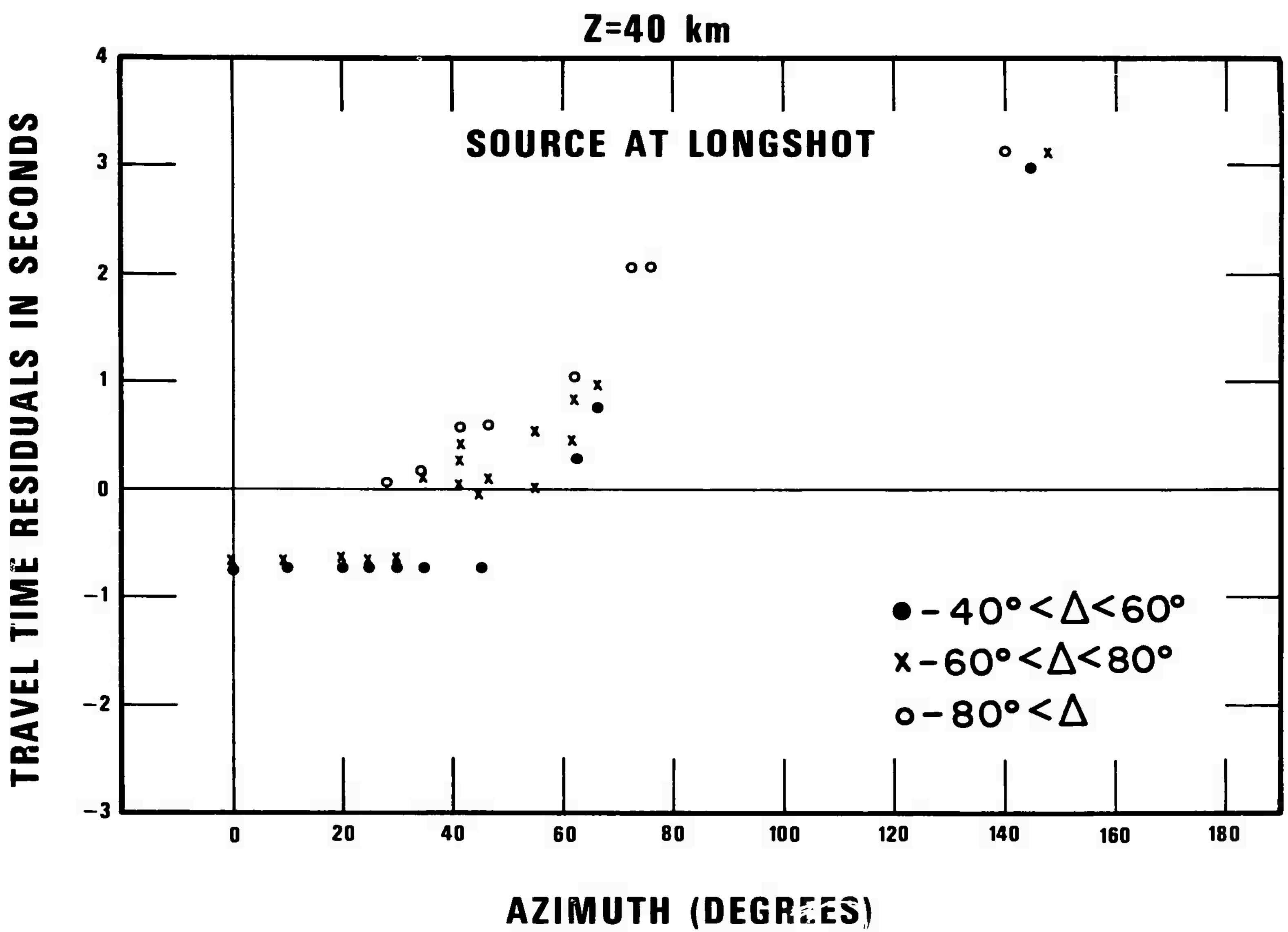


Figure 11b. Calculated residuals vs azimuth.

16K

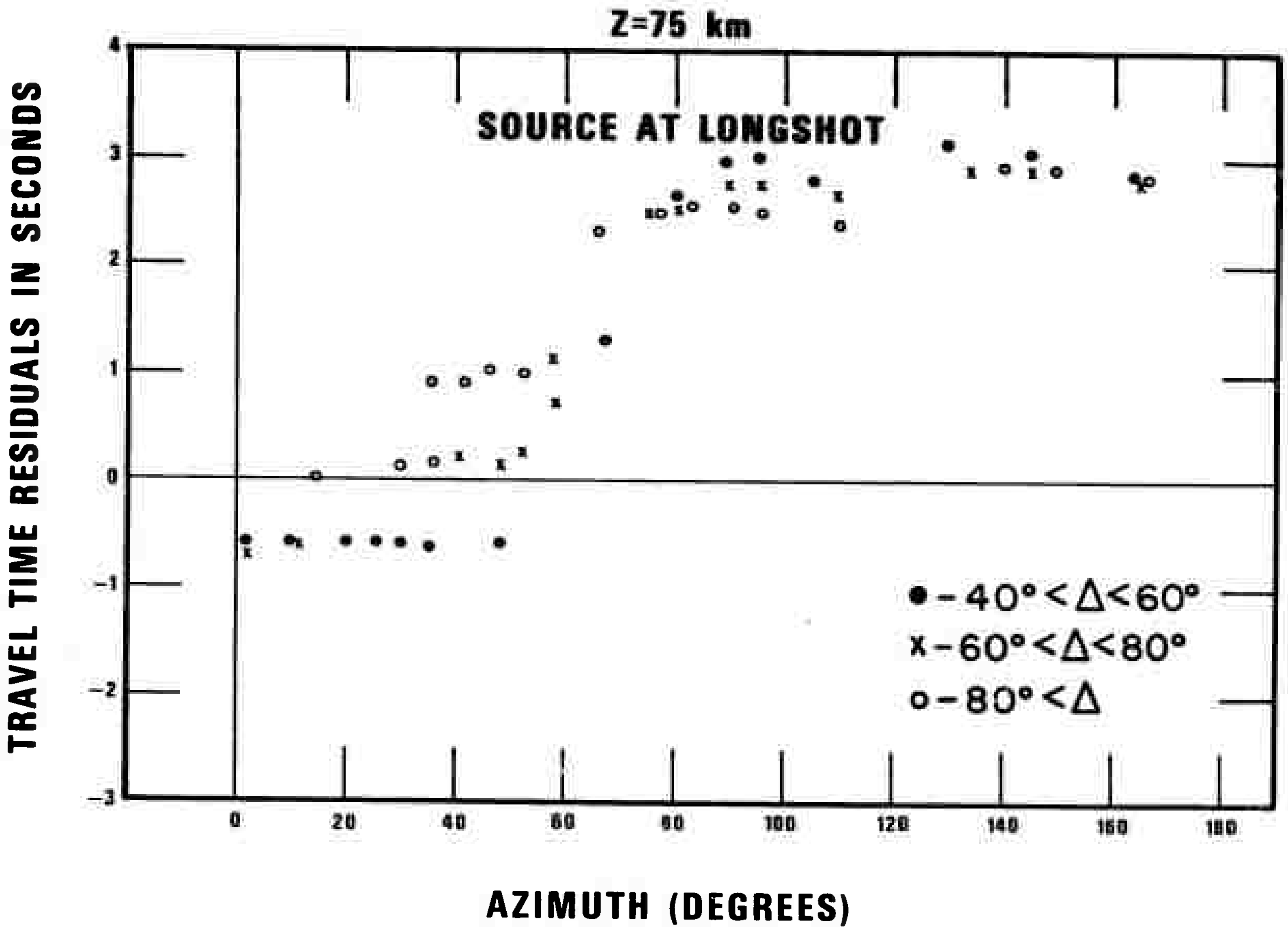


Figure 11c. Calculated residuals vs azimuth.

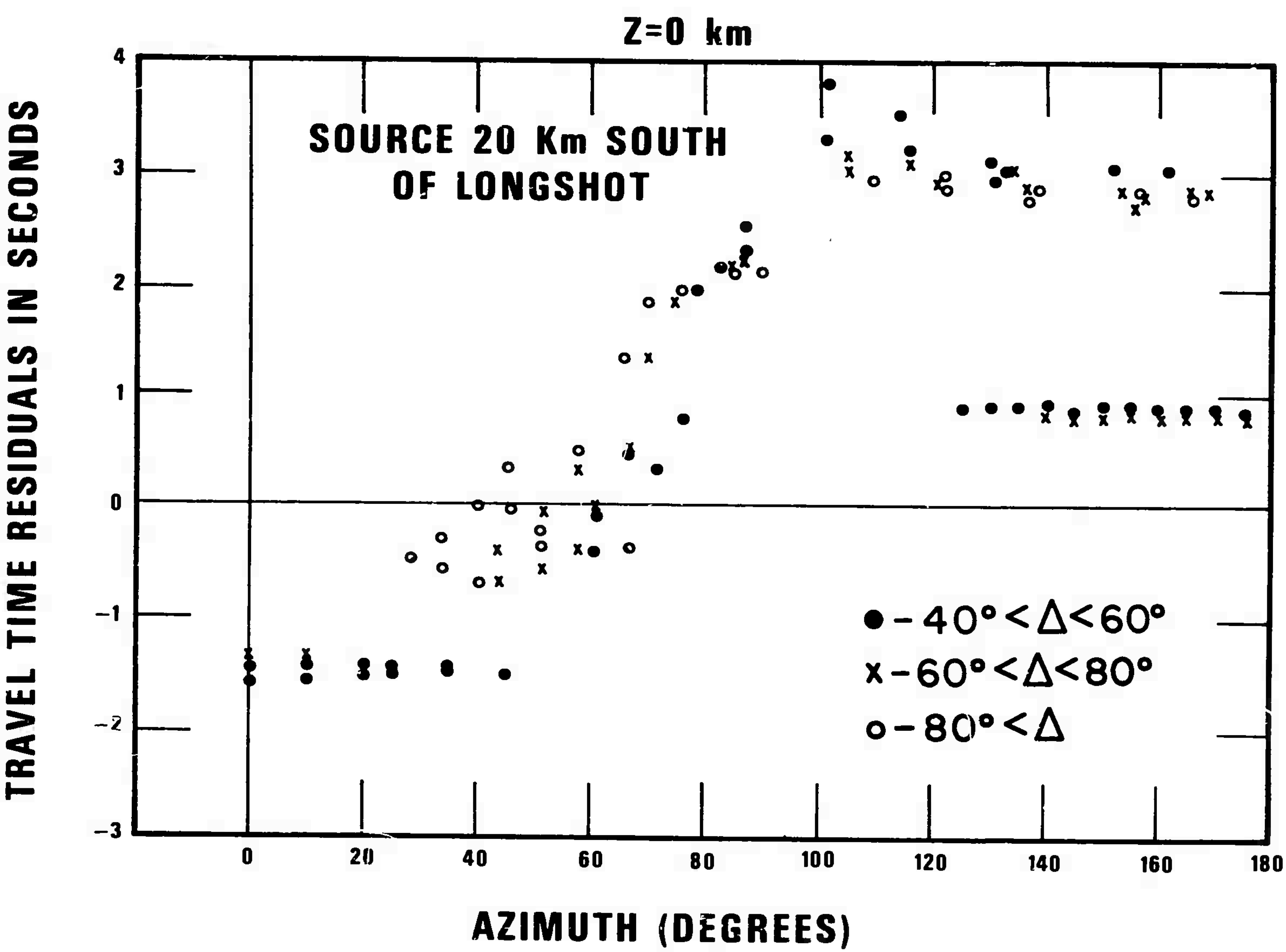


Figure 12. Calculated residuals vs azimuth.

16M

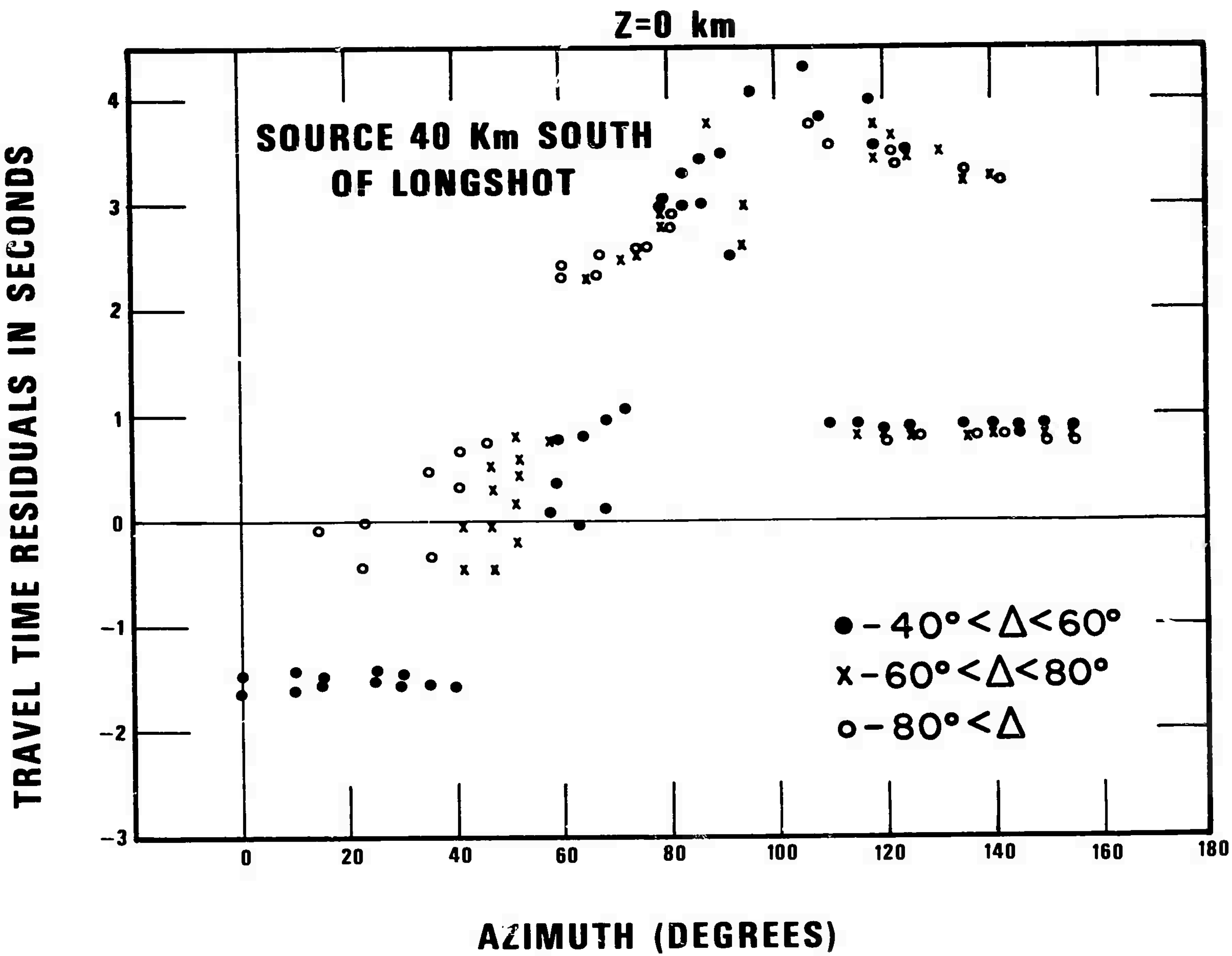


Figure 13. Calculated residuals vs azimuth.

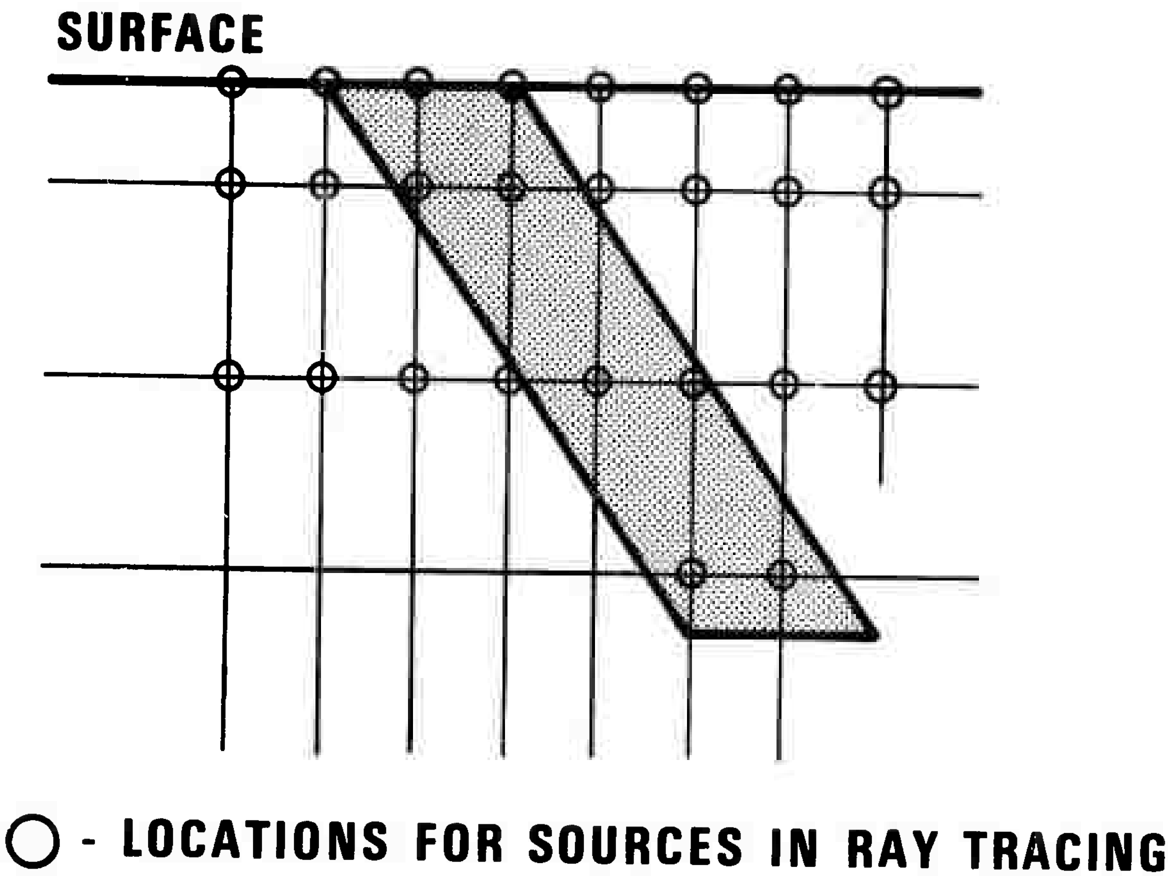


Figure 14. Source locations for ray tracing.

Residuals for epicentral distances 40° $<\Delta<$ 60°, 60° $<\Delta<$ 80°, and $\Delta >$ 80° are plotted as different symbols. The limits of values which the residuals may take for the given distance range are indicated in some cases by two identical symbols corresponding to the same azimuth. Figures 9, 10 and 11 also show the residuals for the depths 40 and 75 Km, on separate figures indicated by subindex. One feature observed from these plots is that as the source moves southward toward the plate, the negative and positive residual increase. The depth dependence is also apparent.

The appearance of "multiple arrivals" in Figures 11a, 12 and 13 apparently are rays which travel north down the plate until they strike its lower boundary, whereupon they are refracted back to a southerly direction. However because the plate is not adequately modeled near the surface, these rays may not actually exist.

Figures 6 and 11b indicate the existance of shadow zones where ray theory predicts no arrivals. The way to predict an arrival time for such zones is indicated in Figure 15. Here the ray-tracing is carried to the point at which a shadow boundary ray has reflected from the plate. This point of reflection is moved just into the plate and considered a new source location. Ray tracing is initiated from this point and the rays from this source which leave the model structure at the same angle as the glancing rays are then considered to

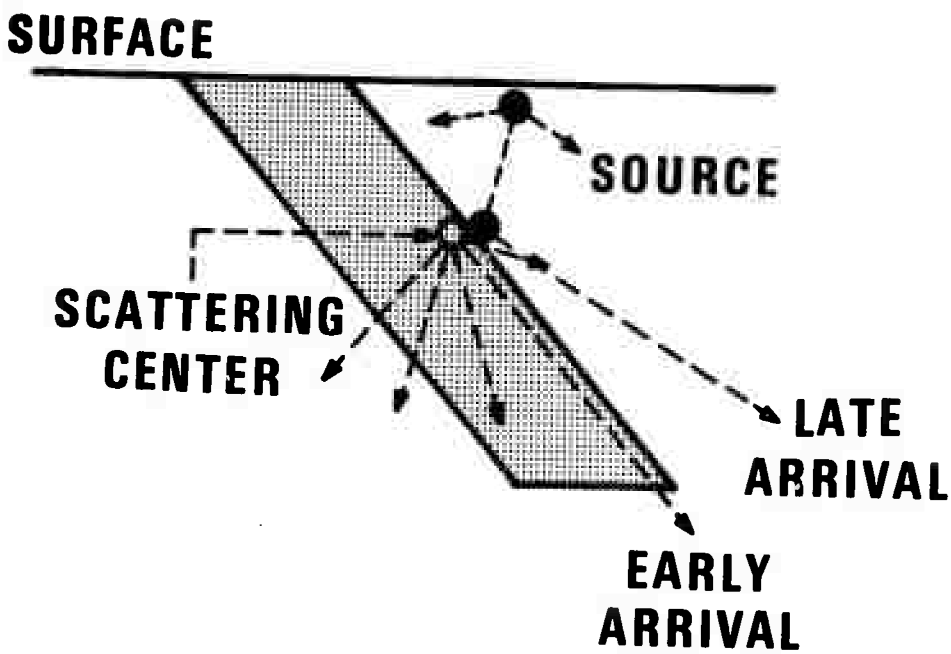


Figure 15. Accounting for energy leakage into plate.

represent the observed earliest arrival. This method has not yet been tried out, but something along this line is needed to insure that one obtains shadow zone arrivals to be used in the location shift calculations.

We propose the following location method for underthrusting plate source regions:

a. Determine a simplified plate model for each region, defining parameters governing plate depth, width, and dip angle; assume a ~10 percent higher velocity in the plate. If possible, determine the model from observed residuals (as Jacobs did).

b. Using this model with the ray-tracing program, determine residuals for a hypothetical world net for different source positions and depths.

c. Using these residuals, use the shift location program to determine the location shift for the various source locations. This shift will be relative to the plate orientation of the particular source region being considered.

d. Because of uncertainty in the assumed plate velocities and geometry, use a calibration event to correct the location shifts determined from the model's residuals to those of the observed location shifts. This gives a correction factor to be used for all source location shifts.

e. Use the initial source location estimate and depths to specify which calculated location shift applies, and then modify this shift using the correction factor.

CONCLUSION

In this report we have presented evidence demonstrating that for teleseismic locations with large networks the source structure is the main source of error for island arc regions. Each of the well-located events in the Aleutian-Alaskan region had location shifts perpendicular to the arc defined by the underthrusting plate. These location shifts are accounted for by plate models of this region. We believe that most of inconsistencies in the location shift patterns for events in the Aleutians as well as in other island arc regions, exist because of inaccurate earthquake locations. There are indications that current knowledge of the plate parameters is sufficient to give good estimates of the location shift magnitude when a single calibration event can be used to account for the uncertainties in plate velocities and geometry. Throughout the region in which the plate has a similar composition, one calibration event should apply for the entire region (~3000 Km is the case of the Aleutians) when used in conjunction with ray tracing for the various source locations. Much work needs to be done to bring this method to a useful state. Refinement of ray tracing techniques is needed such that the low amplitude early arrivals of the so called "shadow zone" can be calculated. As a good test of this location method, one should calculate the magnitude of the location shifts for the six events in central Alaska. This calculation would include accounting for the depth of focus of these events (approximately 100 Km) as well

as the shallower plate dip angle characterizing this region.

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